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ENGINEERING AND DESIGN

# Criteria for Riprap Channel Protection

1. Purpose and Scope. This ETL prescribes guidance and criteria for stone riprap protection for flood channels subject to erosion by flow velocity. The provisions of paragraph 5, Civil Works Engineering Bulletin 52-15, 2 June 1952, were rescinded by EM 1110-2-3901, 4 April 1969. This ETL does not apply to riprap or stone protection for earth dams and embankments, breakwaters and jetties, stilling basins and drop structures, or any other structure designed to provide protection against wave action or energy dissipation. Criteria for riprap protection of these structures are contained in the following Engineering Manuals and Design Criteria Chart:

a. Earth Dams and Embankments. EM 1110-2-2300, "Earth Embankments", 1 April 1959.

b. Breakwaters and Jetties. EM 1110-2-2904, "Design of Breakwaters and Jetties", 30 April 1963.

c. Stilling Basins and Drop Structures. EM 1110-2-1603. "Hydraulic Design of Spillways", 31 March 1965, and "Hydraulic Design Criteria", Chart 712-1.

2. Bases for Riprap Criteria. The criteria presented herein may be classified into two general categories: those which apply to the physical characteristics of the riprap material and those which apply to the stability of the riprap revetment. Criteria pertaining to the physical characteristics of the riprap material are based on field experience and past practice. Criteria for the stability of riprap revetment are based on the analytical determination of shear forces created by channel flow and the ability of the riprap revetment to withstand those forces. Available laboratory data were utilized in developing the analytical method for determining shear forces. While the criteria yields definite sizes and gradations of riprap, these should be used for guidance purposes and revised as deemed practical to provide for such other factors as are discussed herein.

3. Factors Affecting Riprap Revetment Stability. The ability of riprap revetment to resist the erosive forces of channel flow depends on the inter-relation of the following main factors: stone shape, size, weight and gradation; channel side slopes, roughness, shape, alignment and invert slope; and riprap layer thickness. In addition, the manner of placement and treatment of extremities affect the stability of riprap revetment.

4. Stone Shape. Riprap stone should be blocky in shape rather than elongated as more nearly cubical stones "nest" together best and are most resistant to movement. The stone should have sharp, clean edges at the intersections of relatively flat faces. Cobbles with rounded edges are less resistant to movement, although the drag force on a rounded stone is less than on sharp-edged, cubical stones. As the internal friction angle of a graded mass of cobbles is less than an equal mass of cubical stones, the cobbles are more likely to be eroded by channel flow. The following shape limitations should be specified for riprap obtained from quarry operations:

a. The stone shall be predominantly angular in shape.

b. Not more than 25 percent of the stones reasonably well distributed throughout the gradation shall have a length more than 2.5 times the breadth or thickness.

c. No stone shall have a length exceeding 3.0 times its breadth or thickness.

These limitations apply only to the stone within the riprap gradation and not to any quarry spalls and waste which may be allowed. When a high percentage of quarry wastes or spalls are allowed or quarry run stone is used which does not meet the above limitations, an increase in riprap thickness should be provided as prescribed hereinafter in paragraph 10.

5. Stone Size and Weight. The ability of riprap revetment to resist erosion is related to the size and weight of stones. Design criteria may be expressed in terms of the stone weight, $W_{50}$, where the numerical subscript denotes the percentage of the total weight of the graded material, including quarry wastes and spalls, which contains stones of less weight. The relationship between size and weight of stone may be expressed by

$$D_s = \left( \frac{6W}{\pi \gamma_s} \right)^{1/3} \qquad (1)$$

Where $D_s$ is the equivalent-volume spherical stone diameter in feet, W is the stone weight in pounds, and $\gamma_s$ is the saturated surface dry (SSD) specific weight of the stone in pounds per cubic foot. Figure 1 presents relationships between spherical diameter and stone weight for several values of specific weight. Design procedures for determining the stone weight to resist the erosive forces of channel flow are presented in paragraph 8.

6. Channel Side Slopes. The stability of riprap bank revetment is affected by the steepness of channel side slopes. Side slopes on which stone is placed by machine or dumped should not be steeper than 1 on 2. Side slopes for hand placed riprap should not be steeper than 1 on 1.5, except in special cases where it may be economical to use larger stone keyed well into the bank. The size of stone required to resist the erosive forces of channel flow increases with the steepness of side slopes since the stabilizing gravitational force component decreases. The design procedure for determining the affect of channel side slopes on stone size is presented in paragraph 8.

7. Channel Roughness, Shape, Alignment and Invert Slope. As boundary shear forces depend on channel roughness, shape, alignment and invert slope, these factors must be considered in determining the size of stone required for riprap revetment. In general, shear forces and stone sizes are reduced by increasing the channel roughness, adopting a broad shallow channel with gradual alignment changes, and reducing the invert slope. The use of smaller stone reduces the cost of riprap revetment but other channel costs are increased. Comparative cost estimates should be made for several alternative channel plans to determine the most economical and practical combination of channel factors and stone size.

8. Design Criteria For Stone Weight.

a. General. Riprap protection for a flood control channel is subjected to hydrodynamic drag and lift forces which tend to erode the revetment and reduce its stability. The drag and lift forces, which are created by flow velocities, are proportional to the local boundary shear. Forces resisting motion are the submerged weight of the stone and any downward force component caused by contact with other stones in the revetment. The stability of the riprap revetment, then, depends upon the interaction of the local boundary shear and the size and gradation of the riprap material.

b. Average Boundary Shear. The average boundary shear over the wetted perimeter of a channel cross section is given by

$$\bar{\tau}_o = \gamma RS \tag{2}$$

where $\overline{\tau}_o$ is the average boundry shear in pounds per square foot, $\gamma$ is the unit weight of water in pounds per cubic foot, R is the hydraulic radius in feet, and S is the slope of the energy gradient. By utilizing Chezy's formula and the relationship between the friction coefficient C and the roughness k, equation (2) becomes

$$\overline{\tau}_o = \frac{\gamma V^2}{\left(32.6 \log_{10} \frac{12.2 R}{k}\right)^2} \qquad (3)$$

where V is the average cross-sectional velocity in feet per second and k is the equivalent channel surface roughness in feet.

c. Local Boundary Shear. In a straight trapezoidal channel with equal bottom and side roughness, the boundary shear varies over the wetted perimeter as shown in Figure 2. By substituting in equation (3) the depth y in feet for R, the average local velocity in the vertical $\overline{v}$ for V and the average stone theoretical diameter $D_{50}$ in feet for k, the local boundary shear at any point on the wetted perimeter is given by

$$\tau_o = \frac{\gamma \overline{v}^2}{\left(32.6 \log_{10} \frac{12.2 y}{D_{50}}\right)^2} \qquad (4)$$

The average local velocity in the vertical at any point should be determined as illustrated in OCE draft report "Criteria for Graded Stone Riprap Protection", dated 20 April 1966. When there is a significant difference in roughness over the wetted perimeter, as may occur in a channel with riprap bank revetment and a natural invert, an effective average friction coefficient as determined from Hydraulic Design Chart 631-4 should be used in computing values of $\overline{v}$. A graphical solution of equation (4) is presented in Figure 3.

d. Boundary Shear in Bends. The distribution of local boundary shear in a bend of a trapezoidal channel with equal bottom and side roughness is indicated in Figures 4 and 5. Local boundary shear values obtained by equation (4) should be multiplied by the indicated ratios of $\tau_b / \tau_a$ to obtain local boundary shear values in a bend.

e. Riprap Design Shear. The riprap design shear is defined as that amount of local boundary shear that the in-place riprap will safely withstand. The design shear for riprap placed on an essentially level channel bottom is given by

$$\tau = a \left(\gamma_s - \gamma\right) D_{50} \qquad (5)$$

Where $\gamma_s$ is the unit weight of stone saturated surface dry (SSD) and the coefficient "a" equals 0.040. The design shear for riprap placed on channel side slopes is given by

$$\tau' = \tau \left(1 - \frac{\sin^2 \phi}{\sin^2 \theta}\right)^{0.5} \qquad (6)$$

Where $\phi$ is the angle of the side slope with the horizontal and $\theta$ is the angle of repose of the riprap, normally equal to 40 degrees. Equations (5) and (6) are readily solved by the use of Figures 6 and 7. The local boundary shear at any point on the sides and bottom of a riprap-lined channel should not exceed the design values determined by equations (5) and (6).

9. Stone Gradation. The gradation of stones in riprap revetment affects its resistance to erosion. The stone should be reasonably well graded throughout the in-place layer thickness. Specifications should provide for two limiting gradation curves, and any stone gradation, as determined from a field test sample, which lies within these limits should be acceptable. The gradation limits should not be so restrictive that stone production costs would be excessive. The choice of limits also depends on the underlying filter requirements if a graded stone filter is used. Criteria for filter requirements are given in EM 1110-2-1901. The following criteria provide guidelines for establishing gradation limits.

a. The lower limit of $W_{50}$ stone should not be less than the weight of stone required to withstand the erosive forces of channel flow, as determined by the procedure given in paragraph 8.

b. The upper limit of $W_{50}$ stone should not exceed that weight which can be obtained economically from the quarry or that size which will satisfy layer thickness requirements specified in paragraph 10.

c. The lower limit of $W_{100}$ stone should not be less than two times the lower limit of $W_{50}$ stone.

d. The upper limit of $W_{100}$ stone should not be more than five times the lower limit of $W_{50}$ stone, exceed that size which can be obtained economically from the quarry, or exceed that size which will satisfy layer thickness requirements specified in paragraph 10.

e. The lower limit of $W_{15}$ stone should not be less than one sixteenth the upper limit of $W_{100}$ stone.

f. The upper limit of $W_{15}$ stone should be less than the upper limit of $W_{50}$ stone as required to satisfy criteria for graded stone filters specified in EM 1110-2-1901.

g. The bulk volume of stone lighter than the $W_{15}$ stone should not exceed the volume of voids in revetment without this lighter stone.

h. $W_0$ to $W_{25}$ stone may be used instead of $W_{15}$ stone in criteria (5), (6) and (7) if desirable to better utilize available stone sizes.

Design memoranda and specifications should indicate the permissible stone gradation limits by a table, illustrated as follows:

| Percent Lighter by Weight (SSD) | Limits of Stone Weight, in lbs. |
|---|---|
| 100 | 260-640 |
| 50 | 130-200 |
| 15 | 40-150 |

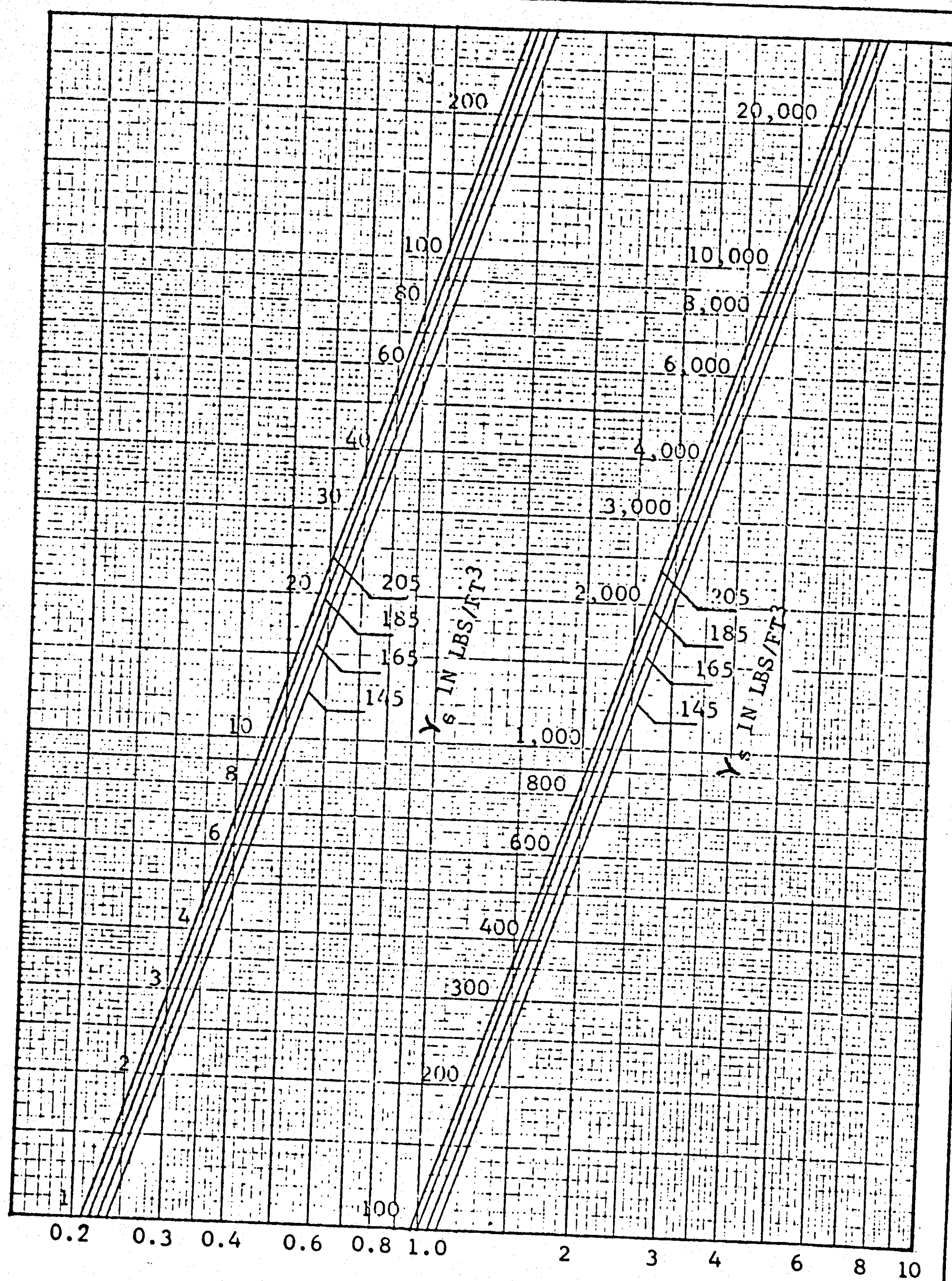
10. Riprap Layer Thickness. All stones should be contained reasonably well within the riprap layer thickness to provide maximum resistance against erosive forces. Oversize stones, even in isolated spots, may cause riprap failure by precluding mutual support between individual stones, providing large voids which expose filter and bedding materials and creating excessive local turbulence which removes smaller stones. Small amounts of oversize stone should be removed individually and replaced with proper size stones. When a quarry produces a large amount of oversize stone, consideration should be given to changing the quarrying method, using a grizzly to remove the oversize stone, obtaining the stone from another source, or increasing the riprap layer thickness to contain the larger stone. The following criteria applies to the riprap layer thickness:

a. It should not be less than the spherical diameter of the upper limit $W_{100}$ stone or less than 1.5 times the spherical diameter of the upper limit $W_{50}$ stone, whichever results in the greater thickness.

b. It should not be less than 12 inches for practical placement.

c. The thickness determined by either a or b should be increased by 50 percent when the riprap is placed under water to provide for uncertainties associated with this type of placement.

d. An increase in thickness of 6 to 12 inches, accompanied by appropriate increase in stone sizes, should be provided where riprap revetment will be subject to attack by large floating debris or by waves from boat wakes, wind, and bed ripples or dunes.

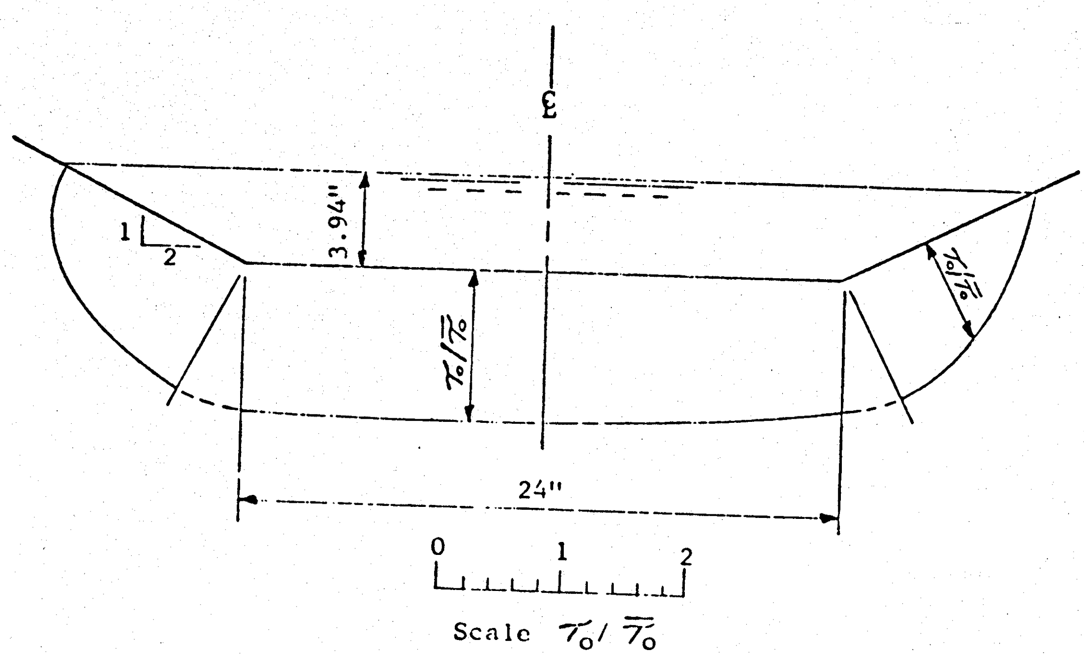



EQUATION:

$W = \gamma_s \pi D_s^3 / 6$ or $D_s = \left( \dfrac{6w}{\pi \gamma_s} \right)^{1/3}$

STONE WEIGHT
VS
SPHERICAL DIAMETER

FIGURE 1
EXHIBIT E




NOTES:

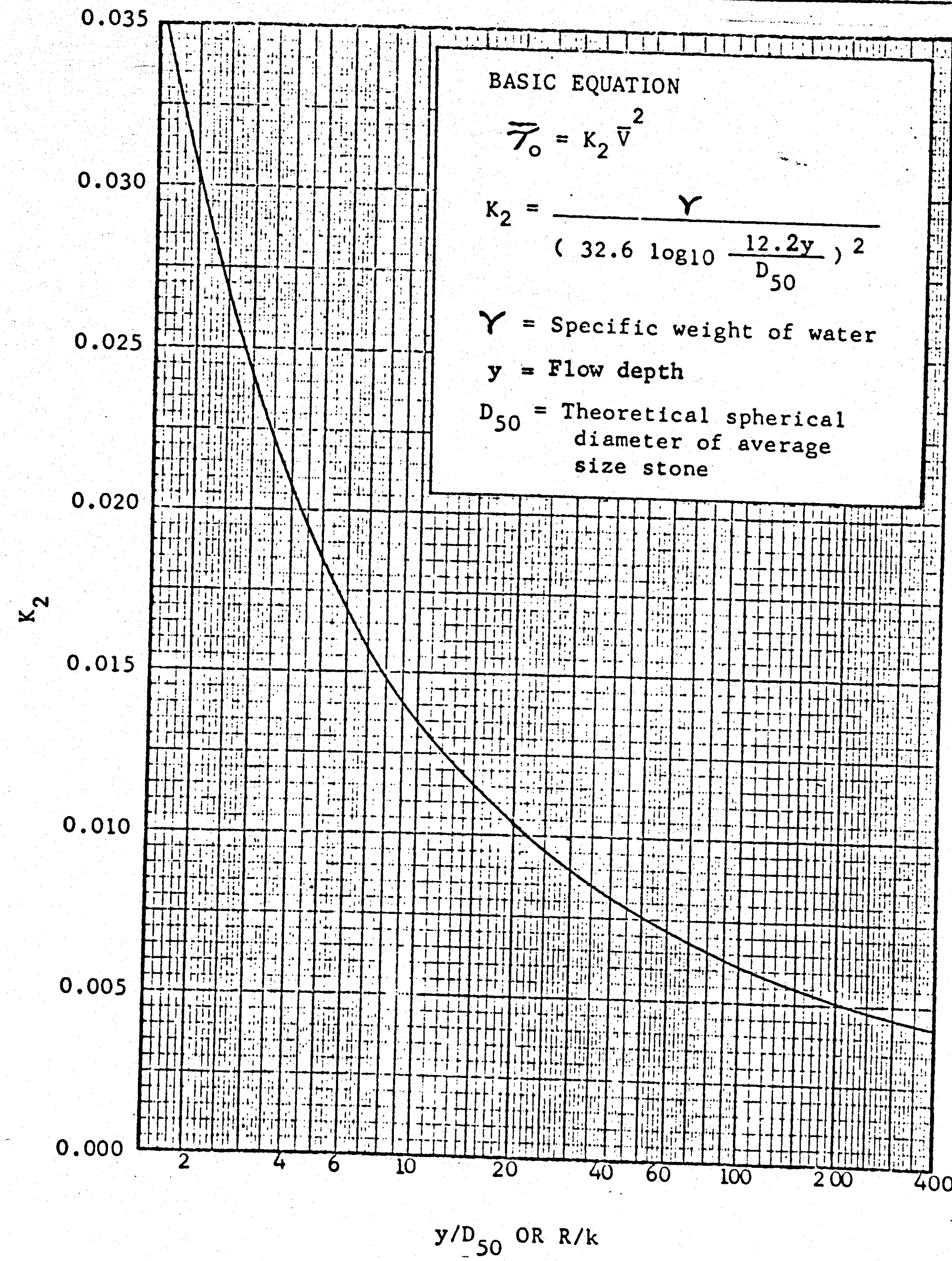
$\bar{\tau}_o$ = average boundary shear in section

$\tau_o$ = local boundary shear

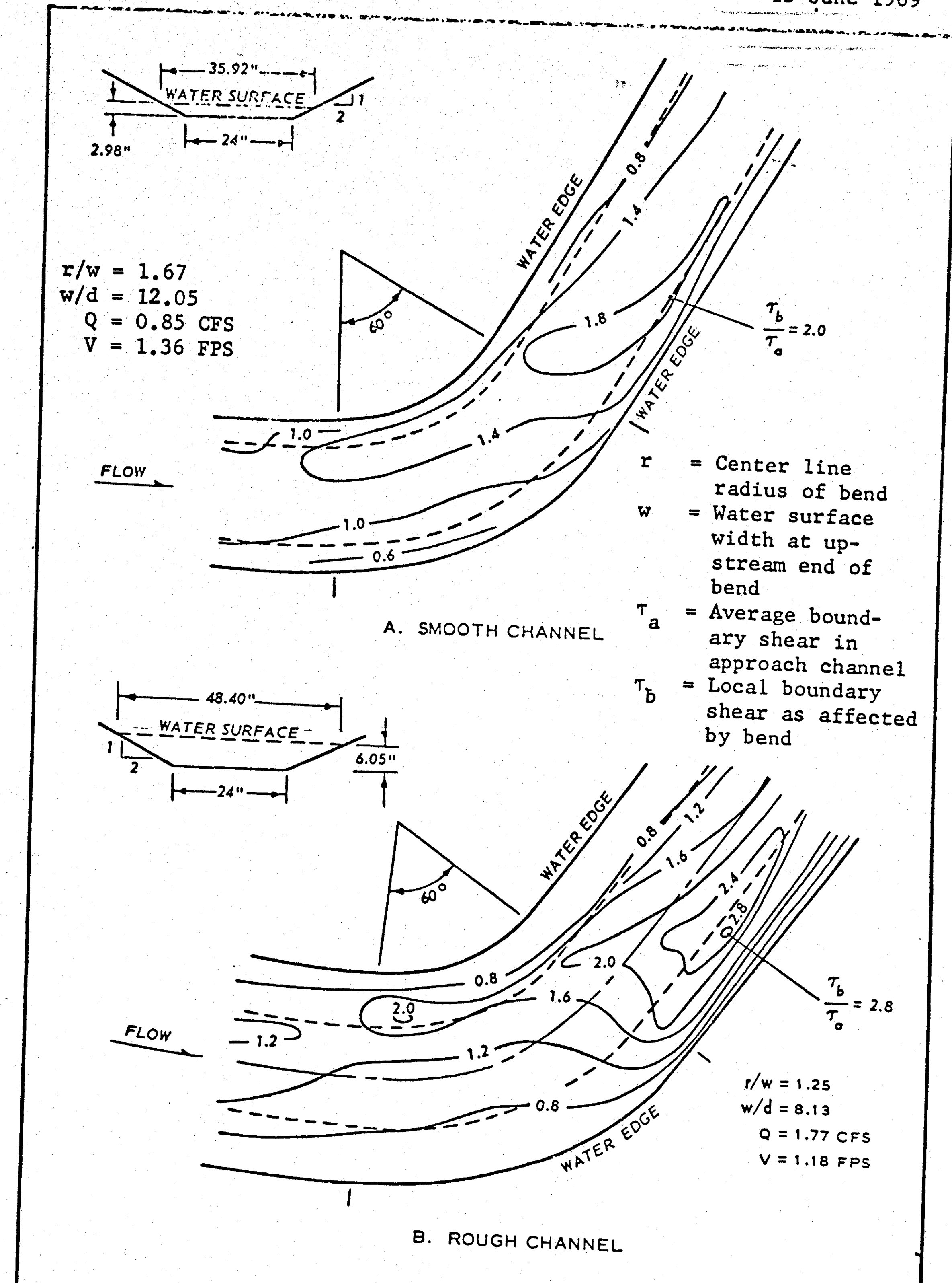
$\tau_{ot}$ = local boundary shear at toe of side slopes

For rough channel, $\tau_{ot} = 1.05\ \tau_o$

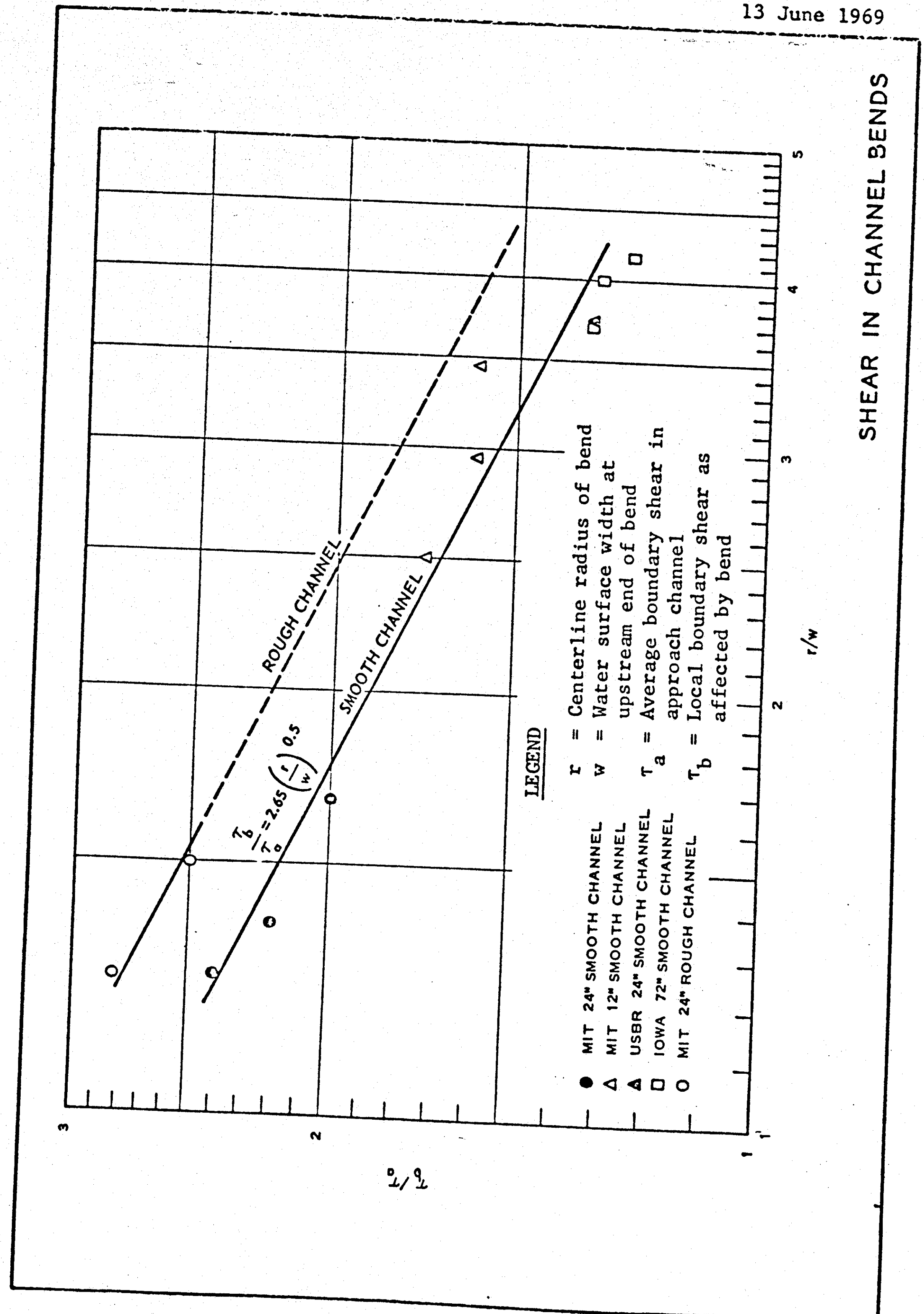
TRAPEZOIDAL CHANNEL
BOUNDARY SHEAR DISTRIBUTION
STRAIGHT REACH



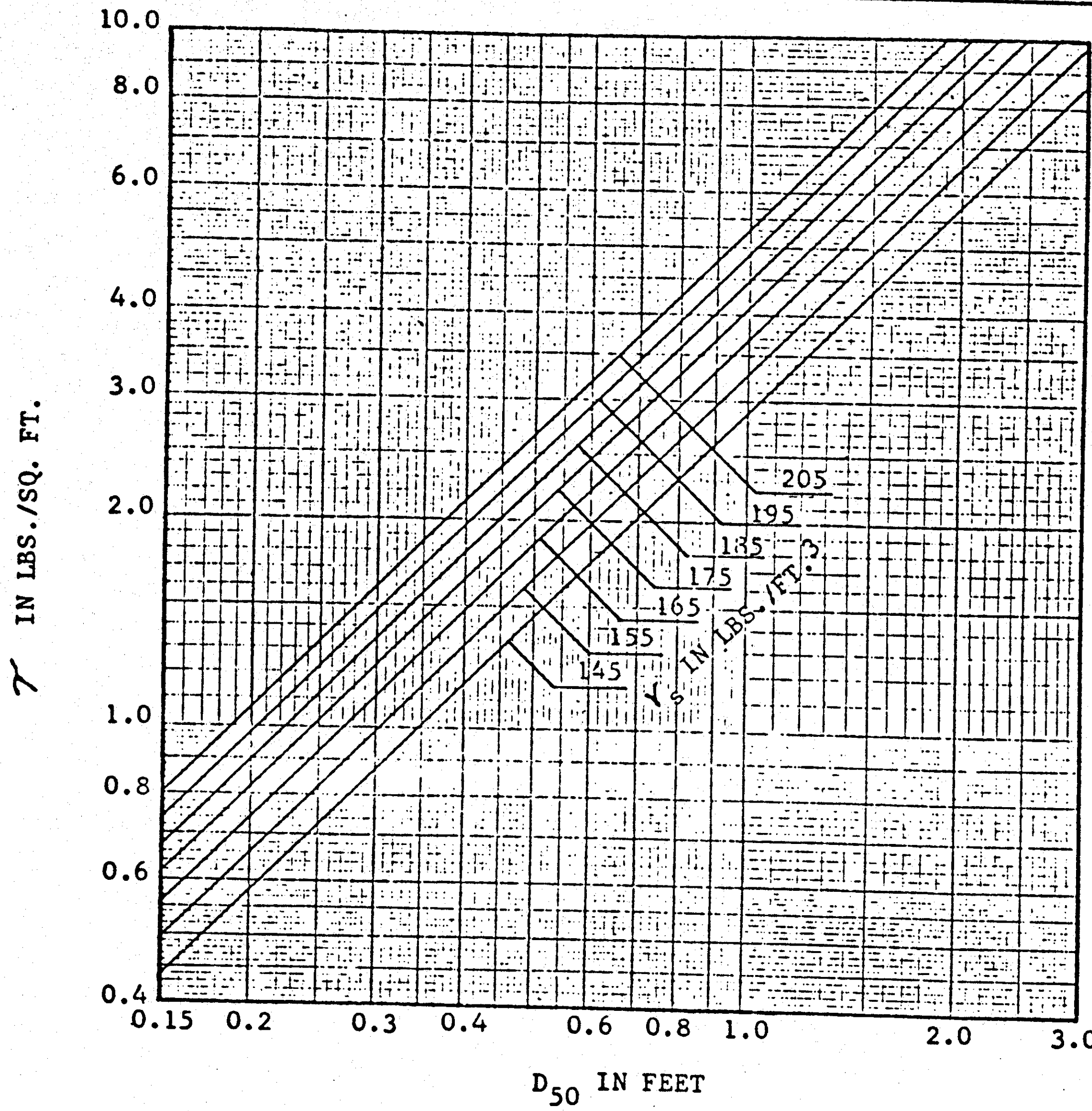

COEFFICIENT $K_2$




CHANNEL BEND EXPERIMENTS
MIT




SHEAR IN CHANNEL BENDS




BASIC EQUATION:

$$\tau = 0.040\ (\gamma_s - \gamma) D_{50}$$

WHERE:

$\tau$ = Design shear force on bottom of channel

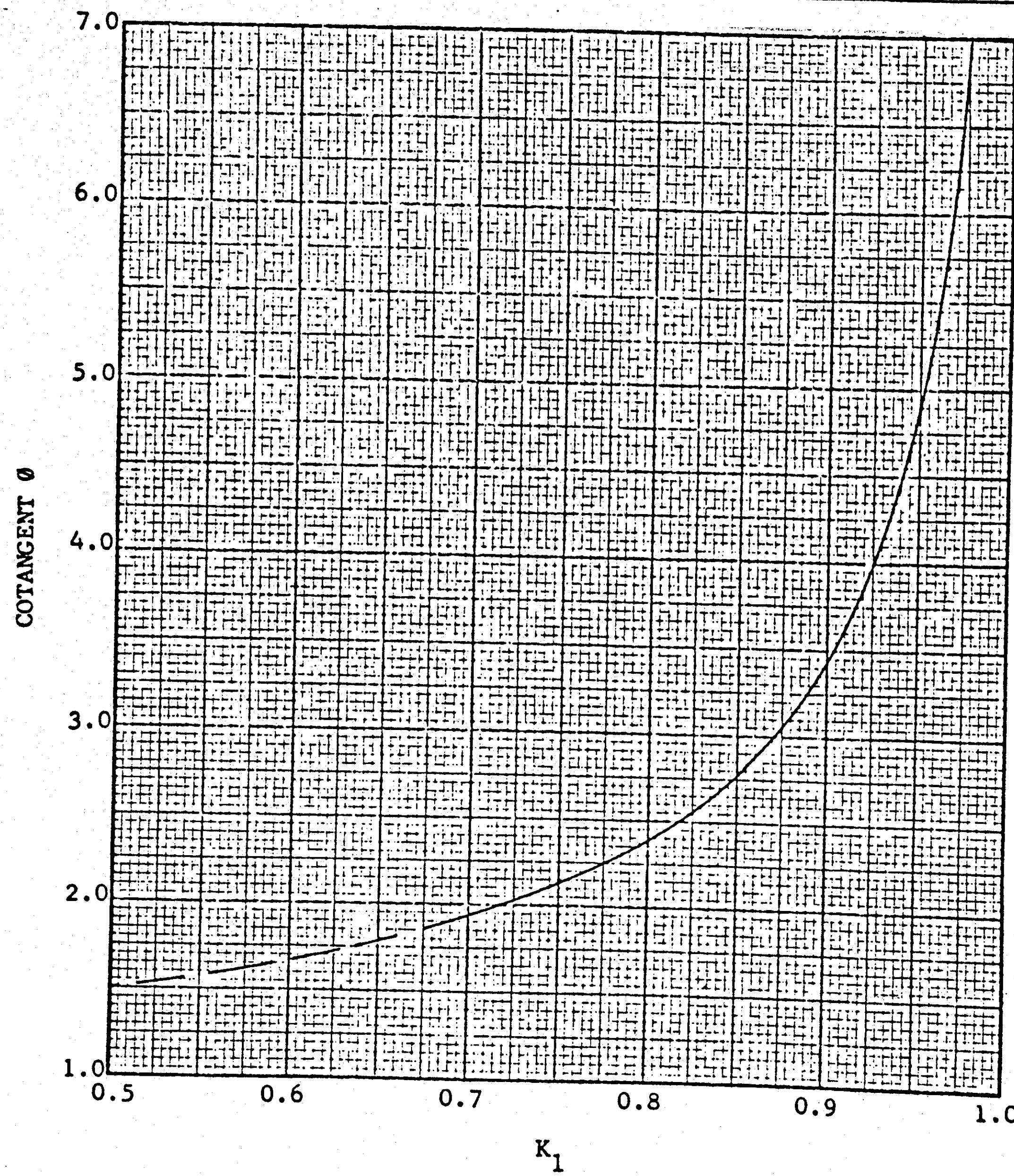
$\gamma_s$ = Specific weight of stone (SSD)

$\gamma$ = Specific weight of water (62.4 lbs/ft.$^3$)

$D_{50}$ = Theoretical spherical diameter of average size stone

DESIGN SHEAR FOR

RIPRAP ON CHANNEL BOTTOM




Ø = Angle of side slope with horizontal

Θ = Angle of repose of material = 40°

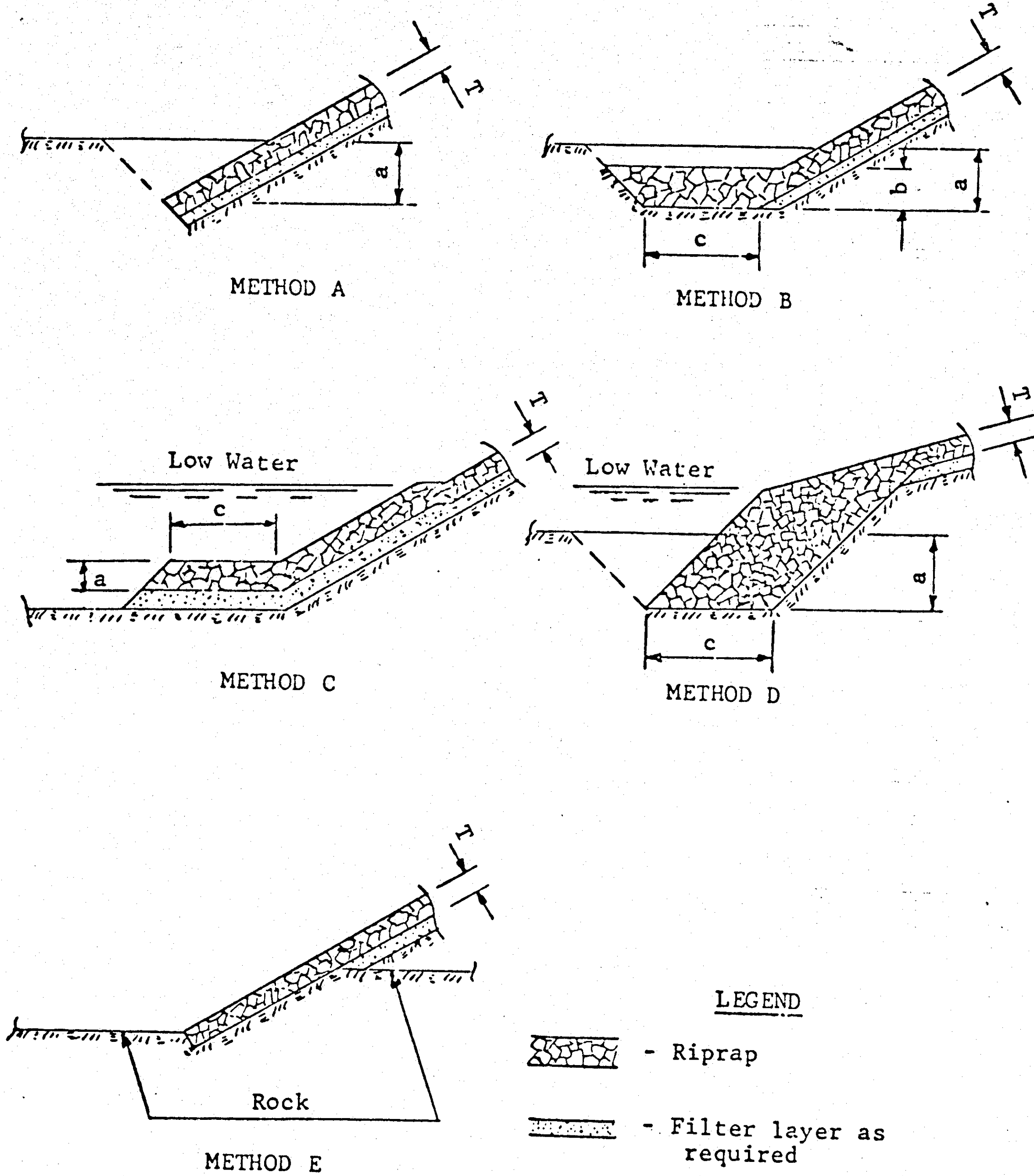
τ = Design shear force on bottom of channel

τ' = Design shear force on side of channel

BASIC EQUATION:

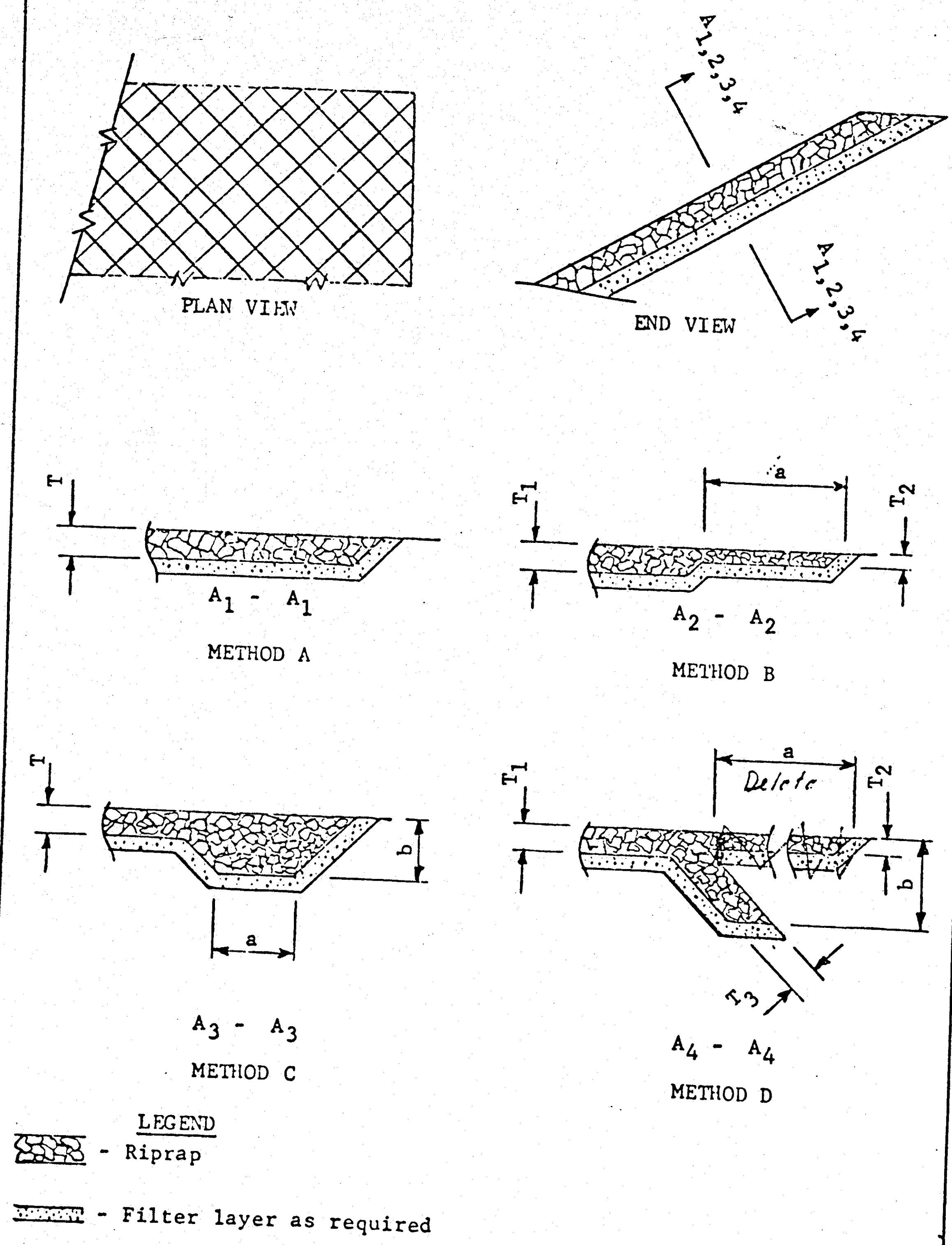
$$K_1 = \frac{\tau'}{\tau} = \left(1 - \frac{\sin^2 \phi}{\sin^2 \theta}\right)^{\frac{1}{2}}$$

RELATIONSHIP BETWEEN BOTTOM AND SIDE DESIGN SHEAR FOR TRAPEZOIDAL CHANNELS




RIPRAP
TOE PROTECTION

FIGURE 8
EXHIBIT E




RIPRAP
END PROTECTION

11. Revetment Toe Protection. As the toe of riprap revetment is subjected to greater erosive forces than other areas, the layer thickness should be increased or the toe should be extended below the anticipated scour depth. The following criteria applies to the alternative methods of toe protection illustrated in Figure 8:

Method A. When toe excavation can be made in the dry, the normal riprap layer should be extended below the existing ground line a distance "a" equal to the anticipated depth of scour.

Method B. When the low-flow or ground-water level is near the existing ground line so that toe excavation is in the wet, a horizontal rock toe should be provided to a depth "a" equal to 3 to 5 feet, a thickness "b" not less than the layer thickness "T", and a base width "c" not less than "a", except that when the anticipated erosion depth is more than 2 or 3 feet below the rock toe, "b" and/or "c" should be increased to provide sufficient stone for adjustment of the toe and protection of the revetment as degradation occurs.

Method C. When the riprap is to be placed under water and design velocities will not cause appreciable streambed erosion, the toe should be placed on the existing channel bottom with "a" and "c" equal to 1.5T and 5T, respectively.

Method D. When the riprap is to be placed under water and appreciable streambed erosion may occur, a thickened rock toe should be placed in a trench with "a" and "c" equal to 3 and 5 T, respectively.

Method E. When the bottom of the channel is in rock, the normal layer of riprap should be keyed into rock at streambed or berm level.

12. Revetment Top and End Protection. Normally, the top lognitudinal extremity of riprap revetment should be terminated at the top of the levee or on the slope at the freeboard level above the design water surface, as shown in end view on Figure 9. Consideration should be given to the economy of terminating the top of the revetment below the levee top or design water surface plus freeboard when the design flood with moderate velocities will overtop the revetment only for a short time. The upstream and downstream ends of riprap revetment should be protected against erosion by increasing the revetment thickness or extending the revetment to areas of non-eroding velocities. The following criteria applies to the alternative methods of end protection illustrated in Figure 9.

Method A. For riprap revetments 12 inches thick, the normal riprap layer should be extended to areas where velocities will not erode the natural channel banks.

Method B. For riprap revetments exceeding 12 inches in thickness, one or more reductions in riprap thickness and stone size may be adopted for a distance "a" in which velocities decrease to a non-eroding natural channel velocity.

Method C. For all riprap revetments which do not terminate in non-eroding natural channel velocities, the ends of the revetment should be enlarged, as shown on Figure 9, with the dimensions "a" and "b" being 3 and 2 times the layer thickness, respectively.

Method D. For riprap revetments exceeding 24 inches in thickness, consideration should be given to the economy of adopting Method D instead of Method C. The stub, with thickness $T_3$ equal to $T_1$, should be placed at the extremity of the revetment proper and the revetment extended a distance "a" with smaller stone size and thickness $T_2$ to a non-eroding location. The depth "b" should equal 2.5 times $T_1$.

13. Riprap Placement. The common methods of riprap placement are hand placing; machine placing, such as from a skip, dragline or some form of bucket; and dumping from trucks and spreading by bulldozer. Hand placement produces the best riprap revetment, but it is the most expensive method except when stone is unusually costly and/or labor unusually cheap. Steeper channel side slopes, requiring smaller volumes of stone, may be used for the hand placement method, but the greater cost of hand placement usually makes machine or dumped placement methods and flatter slopes more economical. Hand placement on steep slopes should be considered when channel widths are constricted by existing bridge openings or other structures and when rights-of-way are costly. In the machine placement method, sufficiently small increments of stone should be released as close to their final positions as practical. Rehandling or dragging operations to smooth the revetment surface tend to result in segregation and breakage of stone and a rough revetment surface. Stone should not be dropped from an excessive height as this may result in the same undesirable conditions. Riprap placement by dumping and spreading is the least desirable method as a large amount of segregation and breakage can occur. In some cases, it may be economical to increase the layer thickness and stone size somewhat to offset the shortcomings of this placement method.

14. Riprap Test Samples. Provisions should be made in the specifications for testing an in-place sample of riprap material as soon as a representative section of revetment has been completed. Additional sample testing of in-place and in-transit riprap material at the option of the contracting officer should be specified. The frequency of sample testing should depend on the ease of producing riprap material

which complies with the specifications. The size of test samples should be sufficient to be representative of the riprap material. Truck-load samples are usually satisfactory for in-transit material. The following table should be used as a guide for the size of in-place samples.

| Riprap Layer Thickness in Inches | Size of Samples in Cu. Yds. Bulk Volume |
|---|---|
| 12 | 1 |
| 18 | 2 |
| 24 | 5 |
| 30 | 10 |
| 36 | 16 |

15. Surveillance. A surveillance program should be established for major riprap bank revetment projects constructed in accordance with criteria furnished in this ETL for the purpose of obtaining data to verify or modify, if necessary, the design criteria. Slope gages and discharge measuring facilities should be installed during project construction. Channel discharges, water-surface elevations, general flow conditions and photographs should be obtained for significant flood flows. Riprap revetments should be inspected after each flood to determine the reasons for and extent of damage, if any. Reports of riprap revetment damage should be prepared and furnished to the Director, Waterways Experiment Station, Attn: WESHP and the Chief of Engineers, Attn: ENGCW-EH after each flood which has resulted in significant revetment damage. The report should contain a description of revetment damage and repairs which were or should be made, reasons for the damages, discharges experienced and condition photographs. The initial damage report for each project should also contain a brief summary of hydrologic and hydraulic design data (discharges, frequencies, water surface elevations, energy gradients, velocities and shear forces), technical information and specifications pertaining to the revetment design and construction and selected contract drawings which show the revetment in plan and section. Design memoranda for flood control channel projects should indicate whether or not provisions will be made for surveillance of riprap revetment.

FOR THE CHIEF OF ENGINEERS:

Wendell E. Johnson

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9 Figures

WENDELL E. JOHNSON
Chief, Engineering Division
Civil Works



EXHIBIT E